Attorney Docket No. 1426/21/2

UNITED STATES PATENT APPLICATION

MICRO-ELECTRO-MECHANICAL SYSTEM (MEMS) VARIABLE CAPACITOR APPARATUSES, SYSTEMS AND RELATED METHODS

Inventors: Francois-Xavier Musalem
Arthur S. Morris III
John R. Gilbert
Siebe Bouwstra
Randy J. Richards

Entity: Small

JENKINS, WILSON & TAYLOR, P.A.
Suite 1400, University Tower
3100 Tower Boulevard
Durham, North Carolina 27707
Telephone: 919-493-8000
Facsimile: 919-419-0383

"Express Mail" mailing number EV 412 572 806 US
Date of Deposit December 15, 2003
I hereby certify that this correspondence is being deposited with the United States Postal Service "Express Mail Post Office to Addressee" service under 37 C.F.R. 1.10 on the date indicated above and is addressed to the Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.
Gayle W. Chaney
Gayle W. Chaney

Description

MICRO-ELECTRO-MECHANICAL SYSTEM (MEMS) VARIABLE CAPACITOR APPARATUSES, SYSTEMS AND RELATED METHODS

Related Application

This application claims the benefit of U.S. Provisional Patent Application Serial No. 60/433,454, filed December 13, 2002; the disclosure of which is incorporated herein by reference in its entirety.

Additionally, co-pending U.S. Patent Application No. 10/461,021, filed June 13, 2003, entitled "Micro-Electro-Mechanical System (MEMS) Variable Capacitor Apparatuses and Related Methods", is incorporated herein by reference in its entirety.

Technical Field

The present subject matter relates generally to micro-electro-mechanical systems (MEMS) apparatuses and methods. More

particularly, the present subject matter relates to variable capacitor apparatuses and related methods utilizing MEMS technology.

Background Art

Micro-electro-mechanical systems (MEMS) apparatuses and methods are presently being developed for a wide variety of applications in view of the size, cost and power consumption advantages provided by these devices. Specifically, a variable capacitor, also known as a varactor, can be fabricated utilizing MEMS technology. Typically, a variable capacitor includes an interelectrode spacing (or an electrode overlap area) between a pair of electrodes that can be controllably varied in order to selectively vary the capacitance between the electrodes. In this regard, conventional MEMS variable capacitors include a pair of electrodes, one that is typically disposed upon and fixed to the substrate and the other that is typically carried on a movable actuator or driver. In accordance with MEMS technology, the movable actuator is typically formed by micromachining the substrate such that very small and very precisely defined actuators can be constructed.

As appreciated by persons skilled in the art, many types of MEMS variable capacitors and related devices can be fabricated by either bulk or surface micromachining techniques. Bulk micromachining generally involves sculpting one or more sides of a substrate to form desired three dimensional structures and devices in the same substrate material. The substrate is composed of a material that is readily available in bulk form, and thus ordinarily is silicon or glass. Wet and/or dry etching techniques are employed in association with etch masks and etch stops to form the microstructures. Etching is typically performed through the backside of the substrate. The etching technique can generally be either isotropic or anisotropic in nature. Isotropic etching is insensitive to the crystal orientation of the planes of the material being etched (e.g., the etching of silicon by using a nitric acid as the etchant). Anisotropic etchants, such as potassium hydroxide (KOH), tetramethyl ammonium hydroxide (TMAH), and ethylenediamine pyrochatechol (EDP), selectively attack different crystallographic orientations at different rates, and thus can be used to define relatively accurate sidewalls in the etch pits being created. Etch

masks and etch stops are used to prevent predetermined regions of the substrate from being etched.

On the other hand, surface micromachining generally involves forming three-dimensional structures by depositing a number of different thin films on the top of a silicon wafer, but without sculpting the wafer itself. The films usually serve as either structural or sacrificial layers. Structural layers are frequently composed of polysilicon, silicon nitride, silicon dioxide, silicon carbide, or aluminum. Sacrificial layers are frequently composed of polysilicon, photoresist material, polimide, metals, or various types of oxides, such as PSG (phosphosilicate glass) and LTO (low-temperautre oxide). Successive deposition, etching, and patterning procedures are carried out to arrive at the desired microstructure. In a typical surface micromachining process, a silicon substrate is coated with an isolation layer, and a sacrificial layer is deposited on the coated substrate. Windows are opened in the sacrificial layer, and a structural layer is then deposited and etched. The sacrificial layer is then selectively etched to form a free-standing, movable microstructure such as a beam or a cantilever out of the structural layer. The microstructure is ordinarily anchored to the silicon

substrate, and can be designed to be movable in response to an input from an appropriate actuating mechanism.

MEMS variable capacitors have been fabricated that include a movable, capacitive plate (or electrode) that is suspended above first and second coplanar electrodes. The variable capacitor operates by applying a voltage across the first electrode and the movable plate so that the plate is deflected towards the first electrode by electrostatic attraction. As the movable plate moves, the spacing between the second electrode and the movable plate changes, thus changing the capacitance value between the second electrode and the plate. A signal line is usually connected to the second electrode and the plate to sense the change in capacitance for use in various Radio Frequency functions. One problem with this configuration is that the voltage supply is electrically connected to the signal line through the plate that can result in undesirable noise/interference or degradation of the signal on the signal line. Thus, this configuration may require additional components to combine/separate the signal and actuation voltage, leading to a more complex and costly implementation. Another problem is that the RF voltage exerts an equivalent force on the movable plate to

that exerted by the intended control voltage, leading to control complexity and increased intermodulation.

Other known MEMS variable capacitors provide parallel-plate electrodes that move linearly. The electrodes of these variable capacitors are subject to suddenly "snapping down" towards one another after moving close enough to one another. These types of variable capacitors are also subject to microphonics and stiction problems.

Some MEMS variable capacitors are based upon electro-thermally actuated parallel-plate design. These types of variable capacitors are subject to reduced power handling capability due to gap reduction and the likelihood for breakdown occurrence. These variable capacitors also consume excessive power, especially if the electro-thermal actuation must be applied continuously to maintain the capacitance value.

Other MEMS variable capacitors utilize a massively-parallel, interdigited-comb device for actuation. These variable capacitors are so sensitive to parasitic substrate capacitance that they require either a high-resistivity substrate such as glass or the removal of the substrate beneath the MEMS device. Thus, this type of variable

capacitor is not readily integrated into a conventional integrated circuit (IC) process. Additionally, the MEMS device is physically large because the capacitance dependence on the overlap of comb fingers requires large aspect ratios. These devices require excessive space and cause a low resonant frequency resulting in shock and vibration problems.

Therefore, it is desirable to provide novel variable capacitor apparatuses and related methods for MEMS applications that improve upon aforementioned designs.

Summary

It is an object to provide a MEMS variable capacitor for electrically isolating the capacitive and actuation plates. It is also an object to provide a MEMS variable capacitor for reducing electrostatic instability. Further, it is an object to at least partially mechanically decouple the movable capacitive and actuation plates of a MEMS variable capacitor. It is therefore an object to provide novel MEMS variable capacitor apparatuses and related methods.

Some of the objects of the present disclosure having been stated hereinabove, and which are addressed in whole or in part by

the present disclosure, other objects will become evident as the description proceeds when taken in connection with the accompanying drawings as best described hereinbelow.

Brief Description of the Drawings

Exemplary embodiments will now be explained with reference to the accompanying drawings, of which:

Figure 1 is a top view of an exemplary MEMS variable capacitor;

Figure 2A is a cross-section side view of one embodiment of the variable capacitor shown in Figure 1;

Figure 2B is a cross-section side view of an alternative embodiment of the variable capacitor shown in Figure 1;

Figure 2C is a cross-section side view of another alternative embodiment of the variable capacitor shown in Figure 1;

Figure 3 is a cross-sectional side view of the variable capacitor shown in Figure 2A with the voltage applied to a movable actuation electrode and a stationary actuation electrode set greater than 0 Volts;

Figure 4 is a top perspective view of a variable capacitor including a movable component suspended above a substrate;

Figure 5 is a cross-sectional side view of the variable capacitor shown in Figure 4;

Figure 6 is another cross-sectional side view of the variable capacitor shown in Figure 4;

Figure 7 is a top view of variable capacitor shown in Figure 4;

Figure 8 is a top perspective view of the variable capacitor shown in Figure 4 with the voltage applied to the actuation electrodes set to a voltage greater than 0 Volts for overcoming the resistive force of tethers;

Figure 9 is a computer simulation model of the z-displacement of a movable component at its first resonance mode;

Figure 10 is a computer simulation model of the z-displacement of a movable component versus actuation voltage;

Figure 11 is a computer simulation model of the z-displacement of movable component for an actuation voltage of about 25 Volts;

Figure 12 is a graph showing capacitance (pF) between stationary capacitive electrode and movable capacitive electrodes versus voltage applied to electrodes shown in Figure 5;

Figure 13A is a computer simulation model of the deformation of movable component for a residual stress value of 120 MPa;

Figure 13B is a computer simulation model of deformation of a movable component under a stress gradient between +10 and -10 MPa;

Figure 14 is a computer simulation model of an equivalent circuit of the variable capacitor shown in Figure 4;

Figure 15A, 15B, and 15C are computer simulation models of deformation of movable component under a stress gradient between +10 and -10 MPa;

Figure 16 is a computer simulation model of an exemplary elliptically-shaped interior portion with the same area under the same stress gradients;

Figure 17 is a computer simulation model of the deformation of an interior portion for an acceleration of 100g;

Figure 18 is a graph showing different tether lengths and peripheral portion widths versus actuation voltage for a variable capacitor;

Figure 19 is a graph showing different tether lengths and peripheral portion widths versus resonance frequency for a variable capacitor;

Figure 20 is a computer simulation model of the z-displacement of the first resonance mode of a variable capacitor having a tether length of 75 micrometers and peripheral portion width of 75 micrometers;

Figure 21 is a computer simulation model of the z-displacement of a variable capacitor having a tether length of 75 micrometers and peripheral portion width of 75 micrometers at an actuation voltage set at 14 Volts;

Figure 22 is a graph showing displacement of the center of a variable capacitor having a tether length of 75 micrometers and peripheral portion width of 75 micrometers versus voltage applied to the actuation electrodes;

Figure 23 is a computer simulation model of the z-displacement of an interior portion of a variable capacitor exposed to a temperature difference;

Figure 24 is another computer simulation model of the z-displacement of an interior portion of a variable capacitor exposed to a temperature difference;

Figure 25 is a computer simulation model of the deformation of an interior component having a tether length of 75 micrometers and peripheral portion width of 75 micrometers for an acceleration of 100g;

Figure 26 is a top perspective view of another exemplary variable capacitor;

Figure 27A is a cross-sectional side view of one aperture;

Figure 27B is a cross-sectional side view of another aperture;

Figure 28 is a graph showing the cut-off frequency of a variable capacitor versus the number of apertures in an interior portion of the variable capacitor;

Figure 29 is a graph showing the damping and tether forces versus frequency for different number of apertures;

Figure 30 is a graph showing the damping coefficient as a function of the frequency for different numbers of apertures;

Figure 31 is a graph showing harmonic analysis of a variable capacitor having an interior portion with 37 apertures;

Figure 32 is a graph showing the cut-off frequency for different aperture numbers;

Figure 33 is a graph showing the effective area of the capacitive electrode as a function of the number of apertures for four different cases according to the minimum distance between the gold layer and the opening of an interior portion;

Figure 34 is a top view of exemplary cascade arrangement of a plurality of variable capacitors;

Figure 35 is a top view of exemplary cascade of plurality of variable capacitors in a fanned-shape arrangement;

Figure 36A is a computer simulation model for an equivalent circuit of four variable capacitors arranged in parallel;

Figure 36B is the RF results of the computer simulation shown in Figure 36B;

Figure 37A is a top perspective view of another exemplary variable capacitor utilizing a rectangular geometry including a suspended, movable component;

Figure 37B is a top perspective view of another exemplary variable capacitor including a suspended, movable component;

Figure 38 is a cross-sectional side view of a variable capacitor having isolation bumps;

Figure 39 is a cross-sectional side view of the variable capacitor shown in Figure 38 when actuation voltage has been applied to the actuation electrodes;

Figure 40 is a cross-sectional side view of another variable capacitor having an isolation bump;

Figure 41 is a cross-sectional side view of another variable capacitor having an isolation bump;

Figure 42 is cross-sectional side view of another variable capacitor having isolation bumps;

Figure 43 is a top perspective view of variable capacitor;

Figure 44A is a cross-sectional side view of the variable capacitor shown in Figure 43;

Figure 44B is a cross-sectional side view of an alternative embodiment of the variable capacitor shown in Figure 43;

Figure 45 is a cross-sectional side view of variable capacitor in an actuated mode;

Figure 46 is a graph showing the harmonic behavior for variable capacitor;

Figure 47 is a graph showing the frequency response for different distances of the movable actuation electrodes and the movable capacitive electrodes shown in Figure 43;

Figure 48 is a top view of a schematic diagram of another examplary torsional variable capacitor;

Figure 49 is a computer simulation model of deformation of a torsional variable capacitor of an array of 16 variable capacitors;

Figure 50 is a graph showing the capacitance of a torsional variable capacitor versus an applied actuation voltage;

Figure 51 is a computer simulation model of deformation of a movable component of a torsional variable capacitor under a stress gradient between +1 and -1 MPa;

Figure 52 is a computer simulation model of the deformation of a movable component in a torsional variable capacitor for an acceleration of 100g;

Figure 53A is a computer simulation model for an equivalent circuit of a torsional variable capacitor; and

Figure 53B is the RF results of the computer simulation model shown in Figure 53A.

Detailed Description

It is understood that when a component such as a layer, substrate, contact, interconnect, electrode, capacitive plate, or conductive line is referred to herein as being deposited or formed "on" another component, that component can be directly on the other component or, alternatively, intervening components (for example, one or more buffer or transition layers, interlayers, electrodes or contacts) can also be present. Furthermore, it is understood that the terms "disposed on", "attached to" and "formed on" are used interchangeably to describe how a given component is positioned or situated in relation to another component. Therefore, it will be understood that the terms "disposed on", "attached to" and

"formed on" do not introduce any limitations relating to particular methods of material transport, deposition, or fabrication.

Contacts, interconnects, electrodes, capacitive plates, conductive lines, and other various conductive elements of various metals can be formed by sputtering, CVD, or evaporation. If gold, copper, nickel or Permalloy™ (Ni_xFe_y) is employed as the metal element, an electroplating process can be carried out to transport the material to a desired surface. The chemical solutions used in the electroplating of various metals are generally known. Some metals, such as gold, might require an appropriate intermediate adhesion layer to prevent peeling. Examples of adhesion material often used include chromium, titanium, or an alloy such as titanium-tungsten (TiW). Some metal combinations can require a diffusion barrier to prevent a chromium adhesion layer from diffusing through gold. Examples of diffusion barriers between gold and chromium would include platinum or nickel.

Conventional lithographic techniques can be employed in accordance with micromachining of the variable capacitors. Accordingly, basic lithographic process steps such as photoresist application, optical exposure, and the use of developers are not

described in detail herein.

Similarly, generally known-etching processes can be employed to selectively remove material or regions of material. An imaged photoresist layer is ordinarily used as a masking template. A pattern can be etched directly into the bulk of a substrate, or into a thin film or layer that is then used as a mask for subsequent etching steps.

The type of etching process employed in a particular fabrication step (e.g., wet, dry, isotropic, anisotropic, anisotropic-orientation dependent), the etch rate, and the type of etchant used will depend on the composition of material to be removed, the composition of any masking or etch-stop layer to be used, and the profile of the etched region to be formed. As examples, poly-etch ($HF:HNO_3:CH_3COOH$) can generally be used for isotropic wet etching. Hydroxides of alkali metals (e.g., KOH), simple ammonium hydroxide (NH_4OH), quaternary (tetramethl) ammonium hydroxide ($(CH_3)_4NOH$, also known commercially as TMAH), and ethylenediamine mixed with pyrochatechol in water (EDP) can be used for anisotropic wet etching to fabricate V-shaped or tapered grooves, trenches or cavities. Silicon nitride is typically used as the masking material against ethcing by KOH, and thus can be used in

conjunction with the selective etching of silicon. Silicon dioxide is slowly etched by KOH, and thus can be used as a masking layer if the etch time is short. While KOH will etch undoped silicon, heavily doped (p++) silicon can be used as an etch-stop against KOH as well as the alkaline etchants and EDP. The preferred metal used to form contacts and interconnects is gold, which is resistant to EDP. The adhesion layer applied in connection with forming a gold component (e.g., chromium) is also resistant to EDP.

It will be appreciated that electrochemical etching in hydroxide solution can be performed instead of timed wet etching. For example, if a p-type silicon wafer is used as a substrate, an etch-stop can be created by epitaxially growing an n-type silicon end layer to form a p-n junction diode. A voltage is applied between the n-type layer and an electrode disposed in the solution to reverse-bias the p-n junction. As a result, the bulk p-type silicon is etched through a mask down to the p-n junction, stopping at the n-type layer. Furthermore, photovoltaic and galvanic etch-stop techniques are also suitable.

Dry etching techniques such as plasma-phase etching and reactive ion etching (RIE) can also be used to remove silicon and its

oxides and nitrides, as well as various metals. Deep reactive ion etching (DRIE) can be used to anisotropically etch deep, vertical trenches in bulk layers. Silicon dioxide is typically used as an etch-stop against DRIE, and thus structures containing a buried silicon dioxide layer, such as silicon-on-insulator (SOI) wafers, can be used as starting substrates for the fabrication of microstructures.

An alternative patterning process to etching is the lift-off process. In this case, the conventional photolithography techniques are used for the negative image of the desired pattern. This process is typically used to pattern metals, which are deposited as a continuous film or films when adhesion layers and diffusion barriers are needed. The metal is deposited on the regions where it is to be patterned and on top of the photoresist mask (negative image). The photoresist and metal on top are removed to leave behind the desired pattern of metal.

As used herein, the term “device” is interpreted to have a meaning interchangeable with the term “component”.

As used herein, the term “conductive” is generally taken to encompass both conducting and semi-conducting materials.

Examples of the methods of the present subject matter will now be described with reference to the accompanying drawings.

Referring to Figures 1-3, different views of an exemplary MEMS variable capacitor, generally designated **100**, are illustrated. Figure 1 illustrates a top view of variable capacitor **100** including a movable component **MC** suspended over a substrate (designated **200** in Figure 2A). Movable component **MC** can include a movable actuation electrode **MAE** and a movable capacitive electrode **MCE** disposed on a top surface thereof. Alternatively, movable actuation electrode **MAE** and a movable capacitive electrode **MCE** can be connected to a bottom surface of movable component **MC** or the top and bottom surfaces can each include a movable actuation electrode and a movable capacitive electrode. Additionally, one of movable actuation electrode **MAE** and a movable capacitive electrode **MCE** can be a completely conducting section of movable component **MC** rather than a layer. Movable component **MC** can comprise one or more layers of silica, alumina, un-doped semiconductors, polymers, and other non-conductive materials known to those of skill in the art. The material of movable component **MC** can function to electrically isolate actuation

electrode **MAE** from capacitive electrode **MCE** and provide flexibility for deflecting.

Movable component **MC** can include a plurality of tethers **T1**, **T2**, **T3**, and **T4** connected to movable component **MC** for attaching movable component **MC** to posts (shown in Figure 2A) or other suitable support structures, which may be the structural layer of movable component MC with a step formed by the edge of the sacrificial layer during fabrication. If the process is planarized, the support can be the whole "field" where the top surface is nearly planar. Posts **P1** and **P2** can be rigidly attached to a surface **S** of substrate **200** (shown in Figure 2A). In this embodiment, tethers **T1**, **T2**, **T3**, and **T4** extend along an at least substantially straight line that can be at least substantially perpendicular to a line extending from a center **C** of movable component **MC** to the connection of tether **T1** to movable component **MC**. For example, tether **T1** extends along broken line **102**. Broken line **104** extends from center **C** to the point of attachment for tether **T1** and movable component **MC**. Broken lines **102** and **104** are at least substantially perpendicular. Alternatively, broken lines **102** and **104** can be at other suitable angles with respect to one another. Tethers **T1**, **T2**,

T3, and **T4** can function as stress decouplers, in order to reduce the effects of in-plane stresses such as residual stress, mounting stress and thermal expansion mismatch stress. Additionally, tethers **T1**, **T2**, **T3**, and **T4** can reduce the impact of the gradient of the out-of-plane distribution of these in-plane stresses. Tethers **T1**, **T2**, **T3**, and **T4** can also reduce the impact of the average of the out-of-plane distribution. This results in making variable capacitor **100** less sensitive to process tolerances related to stress control. A voltage supply and signal line can be used to connect movable actuation electrode **MAE** and movable capacitive electrode **MCE** as shown with reference to subsequent figures.

Figure 2A illustrates a cross-sectional side view of one embodiment of variable capacitor **100**. Variable capacitor **100** can include substrate **200** comprising one or more layers, composites, or other combinations of silicon, alumina, silica, polymers and other suitable substrate materials known to those of ordinary skill in the art. A stationary actuation electrode **SAE** can be formed on surface **104** of substrate and positioned directly beneath movable actuation electrode **MAE**. Electrodes **SAE** and **MAE** can be connected to a voltage supply **VS** via conductive lines **106** and **108**, respectively.

Voltage supply **VS** can apply a voltage across electrodes **SAE** and **MAE**. An equal and opposite electrical charge develops on electrodes **SAE** and **MAE** upon the application of a voltage. The equal and opposite electrical charge causes an electrostatic force to pull movable actuation electrode **MAE**, and movable component **MC**, towards stationary actuation electrode **SAE** in a direction indicated by direction arrow **110**. Tethers **T1**, **T2**, **T3**, and **T4** can produce a biasing force to oppose movement of movable component **MC** in direction indicated by arrow **110**. Movable component **MC** can move towards substrate **200** only when the voltage applied across electrodes **SAE** and **MAE** is great enough to overcome the resistive force of tethers **T1**, **T2**, **T3**, and **T4**. The voltage applied across electrodes **SAE** and **MAE** can be increased to deflect electrode **MAE** closer to electrode **SAE** than another position. Thus, the gap distance between electrodes **SAE** and **MAE** can be adjusted by controlling the voltage output by voltage supply **VS**. The voltage applied by voltage supply **VS** can be varied directly by an operator or other suitable electrical circuitry known to those of skill in the art for controlling the voltage output by a voltage supply.

Movable component **MC** is shown in position when the voltage applied by voltage supply **VS** is 0 volts.

Variable capacitor **100** can also include a stationary capacitive electrode **SCE** attached to a base portion **112** disposed on substrate **200**. Stationary capacitive electrode **SCE** can be positioned closer to movable component **MC** than stationary actuation electrode **SAE**, spaced apart vertically from stationary actuation electrode **SAE**, and immediately above base portion **112**. Electrode **SCE** can be positioned directly below electrode **MCE**. Electrodes **SCE** and **MCE** can be electrically connected to a signal line **SL** for supplying a signal, typically AC, to variable capacitor **VC** from other electrical circuitry (not shown). Signal line **SL** can comprise of a highly-conductive metal such as gold, aluminum, silver, copper, or the like. Signal line **SL** can be connected to a high-frequency distribution network with minimum fixed capacitance. Typically, the electrical circuitry connected to signal line **SL** is sensitive to capacitance of variable capacitor **100**. Capacitive electrodes **MCE** and **SCE** can be moved to different positions with respect to one another when voltage is applied to actuation electrodes **MAE** and **SAE** for moving movable component **MC**. Capacitive electrodes **SCE** and **MCE** and

actuation electrodes **SAE** and **MAE** can comprise any suitable type of metal, semi-metal, or doped semiconductor. Capacitive electrodes **SCE** and **MCE** can comprise a highly conductive metal, such as copper, gold, silver, aluminum, or the like.

Figure 2B illustrates a cross-sectional side view of an alternative embodiment of variable capacitor **100**. In this embodiment, movable component **MC** comprises a first portion **200** and a second portion **202**, wherein second portion **202** is positioned closer to substrate **102** than first portion **200**. Therefore, movable actuation electrode **MAE** and stationary actuation electrode **SAE** can be positioned further apart than the distance between movable capacitance electrode **MCE** and stationary capacitance electrode **SCE** to its attachment to first portion **200** because movable actuation electrode **MAE** is positioned on raised first portion **200**. The dual gap can be formed by two different thicknesses of sacrificial layer.

Figure 2C illustrates a cross-sectional side view of another alternative embodiment of variable capacitor **100**. In this embodiment, stationary actuation electrode **SAE** is buried in substrate **102**. Therefore, movable actuation electrode **MAE** and

stationary actuation electrode **SAE** can be positioned further apart than the distance between movable capacitance electrode **MCE** and stationary capacitance electrode **SCE** to its attachment to first portion **200** because stationary actuation electrode **SCE** is buried in substrate **102**. The dual gap can be formed by two different thicknesses of sacrificial layer.

Additionally, in another alternative of Figure 2B, stationary capacitive electrode **SCE** can be positioned parallel with stationary actuation electrode **SAE** on substrate **102** such that electrode **SCE** and **SAE** are not in electrical communication. In this embodiment, the distance between capacitive electrodes **MCE** and **SCE** can be about 0.5 micrometers. Additionally, the distance between actuation electrodes **MAE** and **SAE** can be about 2.0 micrometers.

Referring to Figure 2C illustrates a cross-sectional side view of another alternative embodiment of variable capacitor **100**. In this embodiment, stationary actuation electrode **SAE** is attached directly onto the top surface of substrate **102**. Stationary actuation electrode **SAE** can be buried in substrate **102**. This positioning can increase the distance between stationary actuation electrode **SAE** and movable actuation electrode **MAE** without adding the complexity of

additional sacrificial layers. Substrate **102** can comprise a dielectric or other suitable substrate material.

Figure 3 illustrates a cross-sectional side view of the embodiment of variable capacitor **100** shown in Figure 2A with the voltage applied to electrodes **MAE** and **SAE** set greater than 0 Volts. With the applied voltage set greater than 0 Volts, movable component **MC** can be positioned closer to substrate **200** than when the applied voltage is set to 0 (as shown in Figure 2).

Referring to Figures 4-8, different views of an exemplary hexagonal-shaped implementation of a variable capacitor, generally designated **400**, are illustrated. Figure 4 illustrates a top perspective view of variable capacitor **400** including a movable component **MC** suspended above a substrate **402**. Movable component **MC** can include movable actuation electrodes **MAE1** and **MAE2** and a movable capacitive electrode **MCE1** attached to a top surface **404** of movable component **MC**.

Referring to Figure 4, movable component **MC** can include a peripheral portion **406** and an interior portion **408**. In this embodiment, peripheral portion **406** is hexagonal in shape with a hollow interior for enclosing interior portion **408**. Interior portion **408**

can be attached to peripheral portion **406** with connectors **410** and **412**. There should be at least two connectors according to this embodiment. The exact number of connectors in alternative embodiments can depend on the geometry and design rules of a specific design and process. Peripheral portion **406** can be attached to substrate **402** via a plurality of tethers **T1**, **T2**, **T3**, **T4**, **T5**, and **T6**. Tethers **T1**, **T2**, **T3**, **T4**, **T5**, and **T6** can include ends **414**, **416**, **418**, **420**, **422**, and **424**, respectively, attached to posts (shown in Figure 5). The posts or other support structures can be rigidly attached to substrate **402**.

Figure 5 illustrates a cross-sectional side view of variable capacitor **400**. Variable capacitor **400** can include posts **P1** and **P2** or other suitable support structures for attachment to tethers **T3** and **T6**, respectively. Tethers **T1**, **T2**, **T4**, and **T5** (shown in Figure 4) can also be attached to posts (not shown) such as posts **P1** and **P2** for attachment to substrate **402**. Movable component **MC** can also include movable actuation electrodes **MAE3** and **MAE4** attached to bottom surface **500** and opposing electrodes **MAE1** and **MAE2**, respectively. Movable component **MC** can also include a movable capacitive electrode **MCE2** attached to bottom surface **500** and

opposing electrode **MCE1**. Additionally, a movable actuation electrode (such as movable actuation electrode MAE3) can be positioned on movable component **MC** directly opposing movable capacitive electrode **MCE1**. Electrodes **MAE1** and **MAE3** can be in electrical communication via a conductive interconnect **CI1** extending through movable component **MC**. Electrodes **MAE2** and **MAE4** can be in electrical communication via a conductive interconnect **CI2** extending through movable component **MC**. Electrodes **MCE1** and **MCE2** can be in electrical communication via a conductive interconnect **CI3** extending through movable component **MC**. Electrodes **MAE1, MAE2, MAE3, MAE4, MCE1, MCE2** can comprise the same conductive material and be matched in shape and dimension to its opposing counterpart on movable component **MC** for mechanical stress matching of interior portion **408** (Figure 4) of movable component **MC**. Alternatively, electrodes **MAE1, MAE2, MAE3, MAE4, MCE1, MCE2** can have different suitable shapes and comprise different materials for providing desired stress matching.

Variable capacitor **400** can also include stationary actuation electrodes **SAE1** and **SAE2** positioned on the top surface of

substrate **402** and beneath movable actuation electrodes **MAE1** and **MAE2**, respectively. Alternatively, movable actuation electrodes **MAE1** and **MAE2** can comprise a single actuation electrode as can be appreciated by one of skill in the art. Variable capacitor **400** can also include a stationary capacitive electrode **SCE** positioned on the top surface of substrate **402** and beneath movable capacitive electrode **MCE2**. Movable actuation electrodes **MAE1**, **MAE2**, **MAE3**, and **MAE4** can be connected to a voltage supply **VS** via conductive line **CL1**. Stationary actuation electrodes **SAE1** and **SAE2** can be connected to voltage supply **VS** via conductive line **CL2**. Voltage supply **VS** can apply one voltage potential at movable actuation electrodes **MAE1** and **MAE2** and a different voltage potential at stationary actuation electrodes **SAE1** and **SAE2**. The equal and opposite electrical charge causes an electrostatic force to pull movable actuation electrodes **MAE1**, **MAE2**, **MAE3**, and **MAE4**, and movable component **MC**, towards stationary actuation electrodes **SAE1** and **SAE2** in a direction indicated by direction arrow **502**. Tethers **T1**, **T2**, **T3**, **T4**, **T5**, and **T6** can produce a biasing force to oppose movement of movable component **MC** in direction indicated by arrow **502**. Movable component **MC** can move

towards substrate **402** only when the voltage applied across the stationary actuation electrodes (**SAE1** and **SAE2**) and the movable actuation electrodes (**MAE1**, **MAE2**, **MAE3**, and **MAE4**) is great enough to overcome the resistive force of tethers **T1**, **T2**, **T3**, **T4**, **T5**, and **T6**. Movable component **MC** is shown in position when the voltage applied by voltage supply **VS** is 0 Volts. In this embodiment, when voltage supply **VS** is 0 Volts, movable capacitive electrode **MCE2** is separated from stationary capacitive electrode by about 0.5 micrometers. Additionally, in this embodiment, when voltage supply **VS** is 0 Volts, movable actuation electrodes **MAE3** and **MAE4** can be separated from **SAE2** and **SAE1**, respectively, by about between 1.5 and 2.0 micrometers.

Variable capacitor **400** can also include a stationary capacitive electrode **SCE** attached to the top surface of substrate **402** and beneath movable capacitive electrode **MCE1** and **MCE2**. Electrodes **SCE**, **MCE1**, and **MCE2** can be electrically connected to a signal line **SL** for supplying a signal, typically AC, to variable capacitor **400** from other electrical circuitry (not shown). Movable capacitive electrodes **MCE1** and **MCE2** can be moved to different positions with respect to stationary capacitive electrode **SCE** when

voltage is applied to movable actuation electrodes (**MAE1**, **MAE2**, **MAE3**, and **MAE4**) and stationary actuation electrodes (**SAE1** and **SAE2**) for moving movable component **MC** such that capacitance is changed between movable capacitive electrodes **MCE1** and **MCE2** and stationary capacitive electrode **SCE**.

Referring to Figure 6, another cross-sectional side view of variable capacitor **400** is illustrated. The voltage applied across movable actuation electrodes (**MAE1**, **MAE2**, **MAE3**, and **MAE4**) and stationary actuation electrodes (**SAE1** and **SAE2**) is greater than a 0 Volts for overcoming the resistive force of tethers **T1**, **T2**, **T3**, **T4**, **T5**, and **T6**. With the applied voltage set greater than 0 Volts, peripheral portion **406** can be positioned closer to substrate **402** than when the applied voltage is set to 0 (as shown in Figure 2). Interior portion **408** can also move closer to substrate **402** when peripheral portion **406** is moved towards substrate **402** due to the attachment of interior portion **408** to peripheral portion **406** with connectors **410** and **412**.

Interior portion **408** can be substantially, mechanically isolated from peripheral portion **406** because interior portion **408** is only attached to peripheral portion **406** via connectors **410** and **412**.

Therefore, the deformation of interior portion **408** is substantially limited when its peripheral portion **406** moves towards substrate **402**. If only two connectors are used as in this exemplary embodiment, connectors **410** and **412** can include a cross-sectional area large enough to suppress torsional motion. According to one embodiment connectors **410** and **412** are substantially wider than the thickness of movable component **MC** and substantially shorter than they are wide. Connectors **410** and **412** can range in width between 0.5 micrometers and 100 micrometers. The thickness of movable component **MC** can be between about 0.5 and 20 microns. The width of connectors **410** and **412** can be greater than 5 times the thickness. The length of connectors **410** and **412** can be about 5 micrometers. This is advantageous because interior portion **408** and its attached movable capacitive electrode **MCE** can remain substantially planar when moved towards substrate **402**.

Referring to Figure 7, a top view of variable capacitor **400** is illustrated. Movable capacitive electrode **MCE1** can be connected to signal line **SL** via conduits **C1** and **C2** disposed on top of movable component **MC**. Conduits **C1** and **C2** can extend from movable

capacitive electrode **MCE** along tethers **T6** and **T3**, respectively, for connection to signal line **SL**.

Referring to Figure 7, movable capacitive electrode **MCE1** can have a hexagonal shape with a diameter **d1** of between about 25 micrometers and 2 millimeters. In one embodiment, peripheral component **406** has a width of about 45 micrometers. Alternatively, peripheral component **406** can range between 25 micrometers and 1 millimeter. Tethers **T1**, **T2**, **T3**, **T4**, **T5**, and **T6** can have a length between about 100 and 250 micrometers.

Figure 8 illustrates a top perspective view of variable capacitor **400** with the voltage applied to electrodes **MAE1**, **MAE2**, **MAE3**, and **MAE4** and **SAE** is set to a voltage greater than 0 Volts for overcoming the resistive force of tethers **T1**, **T2**, **T3**, **T4**, **T5**, and **T6**. With the applied voltage set to a voltage greater than 0 Volts, movable component **MC** can be positioned closer to substrate **200** than when the applied voltage is set to 0 (as shown in Figure 2).

Simulations have demonstrated that the embodiment shown in Figures 4-7 can achieve a high impedance control input (with minimum leakage up to about 100 Volts), an operating frequency of between 0 and 10 GHz, a series resistance of less than 0.5 ohms

and typically less than 0.2 ohms, a vibration sensitivity of less than 0.5% capacitance variation for 0.3 g @ 1kHz, and a control input cut-off frequency of greater and 20 kHz.

One important consideration concerns the harmonic behavior of the variable capacitor. The variable capacitor is typically operated in normal air conditions with a very small air gap (between about 0.5 and 0.01 micrometers). When the movable component acts as a piston, the air in the air gap between the movable component and the substrate can act as a squeeze-film and its effects can be strongly dependent on the frequency of the motion. Apertures can be formed in a movable component to reduce the effects of the air in the air gap between the movable component and the substrate.

The quality of resonance (Q) can also be measured for the embodiment shown in Figures 4-7. Generally, Q refers to power dissipation/(energy stored * radian frequency). There are two resonance qualities of interest with regard to this embodiment. One resonance quality of interest is the mechanical quality of resonance of movable component **MC**. This can typically be low due to air damping. However, if it is too low, it will slow down the response of variable capacitor **400**. A mechanical quality Q on the order of unity

is desirable. This can be designed through the gap selected between movable component **MC** and substrate **402** and spacing in movable component **MC** and size/quantities of apertures (described below).

Another resonance quality Q is the electrical resonance quality of variable capacitor **400**. To first order, this resonance quality Q is provided by the following equation:

$$\frac{1}{(\text{radian frequency} * \text{capacitance} * \text{series resistance})}$$

This quality of resonance Q should be as high as possible, such as greater than 100. This can be achieved with a low resistance conduit.

Another key parameter is the tuning ratio which is the ratio between the maximum and minimum capacitances achievable by the variable capacitor. This should be as high as possible with a value greater than 4 being useful and a value greater than 8 considered very desirable. This is achieved by enabling the gap between movable capacitive electrode **MCE** and station capacitive electrode **SCE** to be varied stably over a wide range and by low

parasitics such as fixed capacitances at the edges and at the conduits.

A mechanical resonance frequency calculation can be performed for a small-signal excitation at an "undeformed" state of variable capacitor with voltage set to 0. Damping effects can be considered. Additionally, experiments demonstrate that the variable capacitor embodiment shown in Figure 4-7 can have a resonance frequency above 20 kHz. The first resonance mode occurs at 21.6 kHz. The displacement of movable component **MC** with respect to substrate **402** (z-displacement) for this mode is a "flapping" mode.

Figure 9 illustrates a computer simulation model of the z-displacement of movable component **MC** at the first resonance mode of 21.6 kHz. The edges of movable component **MC** exhibit the largest displacement. The edges are in phase, meaning that the two edges are moving in the same direction. A second resonance mode occurs at 23.4 kHz. The second resonance mode is a "torsional" mode, where the edges move out-of-phase (one edge goes up while the other edge goes down).

Figure 10 illustrates a graph showing displacement of center **C** (μm) of movable component **MC** versus voltage applied to

electrodes **MAE** and **SAE**. Figure 11 illustrates a computer simulation model of the z-displacement of movable component **MC** for an actuation voltage of about 25 Volts. Although a gap ratio of 3 is nominally stable for parallel plate actuation, the deformation of the plates during actuation creates non-planarity and thus introduces instability. This is solved by increasing the gap ratio to grater than 3 to provide margin. However, increasing the gap ratio also increases the control voltage for a given capacitor gap so it should not be increased more than necessary. Typical embodiments have gap ratios of about 4. Deformation is not due to the electrostatic force acting on interior portion **408** (shown in Figure 4), but due to the tilt of peripheral portion **406** (shown in Figure 4) at points where interior portion **408** is attached to peripheral portion **406** (i.e., where connectors **410** and **412** shown in Figure 4 contact interior portion **408**). Bending of moving capacitive electrodes **MCE1** and **MCE2** can have an adverse effect on the capacitance value.

Referring to again Figure 5, any radio frequency (RF) signals on signal line **SL** can generate an electrical force on movable component **MC** due to the electrical charge generated on stationary capacitive electrode **SCE** and movable capacitive electrodes **MCE1**

and **MCE2**. Because the electrical force is related to the square of the voltage and the area of actuation, the AC voltage can introduce a net DC force between stationary capacitive electrode **SCE** and movable capacitive electrodes **MCE1** and **MCE2**. For example, when an RF-signal of 0.5 V_{pp} is applied, the equivalent of a 0.18 DC Volts is applied between stationary capacitive electrode **SCE** and movable capacitive electrodes **MCE1** and **MCE2**. For example, when 15 Volts is applied over an air-gap of 1.5 micrometers, an equivalent pressure of about 885 Pa is generated. In contrast, for example, when 0.18 Volts is applied over an air-gap of 0.5 micrometers, an equivalent pressure of about 1.15 Pa is generated. Even for a displacement as high as 0.4 micrometers, the equivalent pressure of actuation electrodes **MAE1**, **MAE2**, **MAE3**, **MAE4**, **SAE1**, and **SAE2** is about 1645 Pa. In contrast, the equivalent pressure from 0.18 Volts applied over the remaining 0.1 micrometers is 29 Pa. Therefore, movable component **MC** position is primarily determined by actuation voltage until the RF gap is very small as long as the areas of the actuation electrodes are on the order of or significantly larger than the area of the capacitance electrodes.

Figure 12 illustrates a graph showing capacitance (pF) between stationary capacitive electrode **SCE** and movable capacitive electrodes **MCE1** and **MCE2** versus voltage applied to electrodes **SAE1**, **SAE2**, **MAE1**, **MAE2**, **MAE3**, and **MAE4** shown in Figure 5. The minimum capacitance in this embodiment with actuation voltage set at 0 Volts is about 2.1 pF. The capacitance ratio is about 1:3.6.

The robustness of variable capacitor **400** (shown in Figure 4) against residual stress deformations can be a good indicator of the robustness of variable capacitor **400** against temperature changes. Allowing movable component **MC** to rotate to a certain degree generates most of the residual stress effects only in the XY plane. Figures 13A and 13B illustrate different computer simulation models of the deformation of movable component **MC**. Figure 13A illustrates a computer simulation model of the deformation of movable component **MC** for a residual stress value of 120 MPa (uniform stress across movable component **MC**). The displacement in the **x** and **y** directions in this example are smaller than 0.5 micrometers while displacement in the **z** direction is as small as 0.001 micrometers. Thus, the capacitance in this example is not

adversely affected by either the residual stress or the difference in thermal expansion between the movable component **MC** and substrate **402** (shown in Figure 4).

The robustness of movable component **MC** (shown in Figure 4) against stress gradients is also important. As referred to herein, the stress gradient means the varying of the residual and thermal stress levels across the thickness of movable component **MC**. Stress gradients can typically range between 1 and 10 MPa. Figure 13B illustrates a computer simulation model of deformation of movable component **MC** under a stress gradient between +10 and -10 MPa. The warping of interior portion **408** can have a great impact on the capacitance and capacitance ratio of variable capacitor **400** (shown in Figure 4).

Figure 14 illustrates a computer simulation model, generally designated **1400**, of an equivalent circuit of variable capacitor **400** shown in Figure 4. In this example, the SABER™ simulator (available from Analogy, Inc. of Beaverton, Oregon) can be used for modeling variable capacitor **400**. Simulation model **1400** can include six beams for the tethers **1402**, **1404**, **1406**, **1408**, **1410**, and **1412** and associated beams with electrodes **1414**, **1416**, **1418**,

1420, **1422**, and **1424**, respectively. Simulation model **1400** can also include a connector models **1426** and **1428**, and a capacitive electrode model **CEM**.

Figures 15A, 15B, and 15C illustrate computer simulation models of the deformation of different interior portions (such as interior portion **408** shown in Figure 4) under a stress gradient between + and - MPa. Figure 15A illustrates a square-shaped interior portion **1500** under the stress gradient. Figure 15B illustrates a hexagonal-shaped interior portion **1502** under the stress gradient. Figure 15C illustrates a circular-shaped interior portion **1504** under the stress gradient. Table 1 below indicates the maximum and minimum z-displacements for each of the three interior portion shapes.

	Maximum Z	**Minimum Z**	**Delta Z**
square	1.893 µm	-0.804 µm	2.697 µm
hexagon	1.420 µm	-0.933 µm	2.353 µm
circle	1.256 µm	-0.930 µm	2.186 µm

Table 1: Maximum and minimum z-displacements for three interior portion shapes

Based on the simulation results, square-shaped interior portion **1500** provides the largest maximum displacement, which is located at the corners. The center of square-shaped interior portion **1500** provides

the smallest displacement of the three interior portion shapes. This result is explained by the fact that the axis of square-shaped interior portion **1500**, with the same total area, is shorter than for the other two shapes. The average displacement is an indication of the sensitivity of the capacitance to stress gradients. For the maximum displacement, the most robust shape against stress gradient is the circular plate with the hexagonal design of Figure 4 being nearly as good.

An interesting observation is that the iso-displacement curves are elliptical. Figure 16 illustrates a computer simulation model of an exemplary elliptically-shaped interior portion **1600** with the same area under the same stress gradients. In this example, the edges of the ellipse do not move upwards or downwards: the bending of the axis and the bending perpendicular to the axis compensate each other along the elliptical contour. The center of elliptically-shaped interior portion **1700** is almost 1.4 μm below the zero displacement point. The capacitance change is higher in elliptically-shaped interior portion **1700** than in circular-shaped interior portion **1504** (shown in Figure 15C).

A low sensitivity to acceleration is an important requirement for

varactor capacitor. In particular, the change of the capacitance due to vibration or acceleration is expected to be an important source of noise for the variable capacitor. For computer simulations, a constant acceleration was applied to an undeformed interior portion (such as interior portion **408** shown in Figure 4). Several values can be considered, showing a linear behavior of the displacement even for relatively high values of acceleration. Figure 17 illustrates a computer simulation model of the deformation of an interior portion **1700** for an acceleration of 100g. The center displacement of interior portion **1700** is about 0.12 μm. Therefore, the acceleration sensitivity is about 1.2 [nm/g]. For a constant acceleration of 0.3 g, such as the value expected for the vibration, the maximum displacement is only 3.6Å. The capacitance change under these conditions is lower than 0.5%. From the mechanical perspective, the cut-off frequency for the mechanical Low-Pass-Filter can be targeted to be higher than 20 kHz. Therefore, the response of interior portion **1700** to the acceleration will be fairly independent of the frequency, up to 20 kHz. In other words, a vibration of 0.3 g at 1 kHz will provide a capacitance change up to 0.5% of the capacitance.

Table 2 below indicates a summary of specifications for one embodiment of a variable capacitor such as variable capacitor **400** shown in Figure 4.

Parameter	**Value**
$V_{control}$	27 V
Resonance frequency	21.6 kHz
C_{min}	2.2 pF (dc)
Capacitance ratio	maximum 1:3.6
Vibration sensitivity	< 0.5% / 0.3 g

Table 2: Summary of Specifications

The actuation voltage and resonance frequency of a variable capacitor such as variable capacitor **400** (shown in Figure 4) can be dependent upon the width of a peripheral portion (such as peripheral portion **406** shown in Figure 4) and the length of the tethers (such as tethers **T1**, **T2**, **T3**, **T4**, **T5**, and **T6** shown in Figure 4). Figure 18 illustrates a graph showing different tether lengths and peripheral portion widths versus actuation voltage for a variable capacitor (such as variable capacitor **400** shown in Figure 4). Figure 19 illustrates a graph showing different tether lengths and peripheral portion widths versus resonance frequency for a variable capacitor (such as variable capacitor **400** shown in Figure 4). As shown, a variable capacitor having a tether length of 75 micrometers and peripheral

portion width of 75 micrometers can achieve a resonance frequency of 35.9 kHz.

Figure 20 illustrates a computer simulation model of the z-displacement of the first resonance mode of a variable capacitor **2000** having a tether length of 75 micrometers and peripheral portion width of 75 micrometers. The resonance frequency of the first resonance mode is about 33.9 kHz. The resonance frequency of the second resonance mode is about 59.9 kHz. As shown in Figure 20, interior portion **2002** remains relatively rigid and most of the deformation occurs at tethers **T1**, **T2**, **T3**, **T4**, **T5**, and **T6**, along with a tilt in peripheral portion **2004**.

Figure 21 illustrates a computer simulation model of the z-displacement of a variable capacitor **2000** having a tether length of 75 micrometers and peripheral portion width of 75 micrometers at an actuation voltage set at 14 Volts.

Figure 22 illustrates a graph showing displacement of the center of a variable capacitor **2000** having a tether length of 75 micrometers and peripheral portion width of 75 micrometers versus voltage applied to the actuation electrodes.

Figure 23 illustrates a computer simulation model of the z-displacement of an interior portion **2300** of a variable capacitor **2302** exposed to a temperature difference of 100° Celsius. In this example, the z-displacement of interior portion **2300** is about 0.002 micrometers. Therefore, temperature has little effect on the capacitance values in this embodiment.

Figure 24 illustrates a computer simulation model of deformation of an interior component **2400** having a tether length of 75 micrometers and peripheral portion width of 75 micrometers under a stress gradient between +10 and -10 MPa.

Figure 25 illustrates a computer simulation model of the deformation of an interior component **2500** having a tether length of 75 micrometers and peripheral portion width of 75 micrometers for an acceleration of 100g. The z-displacement is less than about 0.03 micrometers for 100g acceleration (i.e., 0.1 nm for an 0.3g acceleration). Therefore, the capacitance can be modified by a factor of about 0.04% with an air gap of 0.26 micrometers.

Referring to Figure 26, a top perspective view of another exemplary variable capacitor, generally designated **2600**, is illustrated. Variable capacitor **2600** can include an interior portion

2602 having a plurality of apertures **2604** extending from a top surface **2606** to an opposing bottom surface (not shown). Apertures **2604** can also extend through a movable capacitive electrode **MCE1** attached to top surface **2606** and a movable capacitive electrode (not shown), if any, attached to the opposing bottom surface (not shown). Apertures **2604** can function to ventilate variable capacitor **2600**. In this embodiment, interior portion **2602** includes thirty-seven apertures that are evenly distributed on surface **2606**. Alternatively, interior portion **2602** can include 7, 27, 169, 721, or any suitable number of apertures.

Referring to Figure 27A, a cross-sectional side view of one aperture, generally designated **2700**, of interior portion **2602** is illustrated. In this embodiment, interior portion **2602** includes movable capacitive electrodes **MCE1** and **MCE2** attached to top surface **2604** and a bottom surface **2702**, respectively. In this embodiment, aperture **2700** is cylindrically-shaped with a diameter of about 5 micrometers. Additionally, in this embodiment, distance **d** between the edges of interior portion **2602** and movable capacitive electrode (**MCE1** or **MCE2**) is between about 0 and 8 micrometers.

Referring to Figure 27B, a cross-sectional side view of another aperture, generally designated **2704**, of interior portion **2706** is illustrated. In this embodiment, a movable capacitive electrode **2708** can extend inside aperture **2704**. Movable capacitive electrode **2708** can conform to and contact movable capacitive electrode **2710**. This embodiment can be advantageous because the area of the capacitive electrode is not reduced as much for a given aperture size.

Figure 28 illustrates a graph showing the cut-off frequency of a variable capacitor versus the number of apertures in an interior portion of the variable capacitor. Extrapolating from the graph, the cut-off frequency is about 20 kHz for 721 apertures.

The number of holes can be selected in order to half the distance between the outer row of holes and the edges of the hexagonally-shaped interior portion at every increment. This leads to a series of the number of holes as follows: 0, 1, 7, 37, 169, 721, etc. At 169 holes, the pitch is 27 micrometers in one embodiment.

Referring to Figure 29, a graph showing the damping and tether forces versus frequency for different number of apertures is

illustrated. In the low-frequency regime, the air acts as a damper. In the high-frequency regime, the air acts as a spring.

Figure 30 illustrates a graph showing the damping coefficient as a function of the frequency for different numbers of apertures. The force at high frequency is relatively independent of the number of apertures because the volume of air being squeezed remains relatively constant.

Figure 31 illustrates a graph showing harmonic analysis of a variable capacitor having an interior portion with 37 apertures. In the low-frequency regime, the variable capacitor is overdamped exhibiting thus a low-pass filter characteristic. At 62 kHz all curves show resonance peaks. The resonance frequencies are determined by the mass of the structures and the combined stiffness of squeezed film and of the solid structure itself. At this pressure (1 bar) and this air gap (0.25 micron) the stiffness of the air is approx. twice the stiffness of the structure itself.

Figure 32 illustrates a graph showing the cut-off frequency for different aperture numbers. Table 3 below indicates the cut-off frequency for different aperture numbers.

Number of Apertures	Cut-off frequency

	[Hz]
1	33
7	51
37	312
169	2420

Table 3: Apertures numbers and Cut-off Frequency

From extrapolation, 17kHz can be expected as a cut-off frequency for 721 apertures. In one embodiment, a distance of 6 micrometers is provided between a capacitive electrode and edge of the interior portion at the aperture. In the configuration of this embodiment, each 5 micrometer diameter hole in the interior portion can have a capacitive electrode opening of 17 micrometers in diameter. Thus, resulting in an effective loss for the capacitance area.

Figure 33 illustrates a graph showing the effective area of the capacitive electrode as a function of the number of apertures for four different cases according to the minimum distance between the gold layer and the opening of the interior portion (8 μm, 6 μm, 2 μm and 0 μm). Regarding 8 μm, the capacitance is reduced by 70% for 25 apertures. Regarding 2 μm, the capacitance is reduced by 40% for 169 apertures. In the embodiment shown in Figure 27B where the aperture is defined by the metal rather than the hole in the structural layer of movable component **MC**, the capacitance can be reduced by less than 15%.

In order to achieve larger capacitance values, the variable capacitor can be made large or two or more variable capacitors can be connected in parallel. The maximum size of the capacitor is constrained by mechanical considerations (including release time, mechanical resonance frequency, damping and stress deformation), and thus the parallel connection of smaller capacitors can be advantageous. Referring to Figures 34 and 35, different top views of exemplary cascade arrangements of a plurality of variable capacitors are illustrated. Referring specifically to Figure 34, variable capacitors **3400** are arranged in a rectangular shape. Referring to Figure 35, variable capacitors **3500** are arranged in a fanned-shape. A signal line (not shown) having a total length of about 600 micrometers and a width of about 5 micrometers (impedance matched to 50 ohms). The inductance inserted by this long signal line can result in a self-resonance frequency in the order of 10 GHz, showing a degradation of the quality factor even at frequencies such as 4 GHz. These interconnects should be kept short as possible. Thus, a center feed to the array is desirable to minimize parasitics and maximize self-resonance frequency.

The variable capacitor arrangements shown in Figures 34 and

35 can have the specifications shown in Table 4 below.

Parameter	Simulated
$V_{control}$	14.6 V
Resonance frequency	33.9 kHz
C_{min}	2.6 pF (neglecting area loss due to apertures)
Capacitance ratio	maximum 1:4
Q	Greater than 35 @ 4.5GHz
Cut-off frequency of the LPF	2.4 kHz (with 169 apertures)

Table 4: Summary of Specifications

Figures 36A and 36B illustrate a computer simulation model, generally designated **3600**, and RF results of computer simulation model **3600**, for an equivalent circuit of four variable capacitors (such as variable capacitor **400** shown in Figure 4) arranged in parallel. Referring to Figure 36A, the HFSS electro-magnetic, full-wave simulator (available from Ansoft Corporation of Pittsburgh, Pennsylvania) can be used for modeling four variable capacitors **3602**, **3604**, **3606**, and **3608**. Model **3600** can include a connection block **3610** representing the connection of variable capacitors **3602**, **3604**, **3606**, and **3608**. Additionally, model **3600** can include a block **3612** representing a line out of the measurement pads.

Referring to Figure 36B, line **3614** shows that the capacitance does vary some with frequency due to the interconnecting scheme. Line **3616** shows the electrical resonance quality Q falling with frequency. In this example, resonance quality Q includes the degrading effects of the interconnects. A Smith chart, generally designated **3618**, shows that the circuit behaves as a capacitor over the whole frequency range.

Figures 37A and 37B illustrate top perspective views of other exemplary variable capacitors. Referring specifically to Figure 37A, a top perspective view of another exemplary variable capacitor, generally designated **3700**, utilizing a rectangular geometry including a suspended, movable component **MC**. Movable component **MC** can include movable actuation electrodes **MAE1** and **MAE2** and a movable capacitive electrode **MCE**. In this embodiment, electrodes **MAE1**, **MAE2**, and **MCE** are attached to a top surface of movable component **MC**. Alternatively, electrodes **MAE1**, **MAE2**, and **MCE** can be attached on the underside of movable component **MC** or on both the top and bottom surfaces. Actuation electrode **MAE1** and **MAE2** and capacitive electrode **MCE** can be electrically isolated via movable component **MC**.

Variable component **3700** can also include tethers **T1**, **T2**, and **T3** attached to movable component **MC** and posts (not shown) for suspending movable component **MC** above a substrate **3702**. Stationary actuation electrodes **SAE1** and **SAE2** can be disposed on the top surface of substrate **3702** and directly beneath movable actuation electrodes **MAE1** and **MAE2**, respectively. A stationary capacitive electrode **SCE** can be disposed on the top surface of substrate **3702** and directly beneath movable capacitive electrode **MCE**. A voltage supply **VS** can be connected at one terminal to movable actuation electrodes **MAE1** and **MAE2** and at another terminal to stationary actuation electrodes **SAE1** and **SAE2**. Voltage supply **VS** can apply a potential difference between the movable actuation electrodes (**MAE1** and **MAE2**) and the stationary electrodes (**SAE1** and **SAE2**) such that, at after a voltage threshold V_T is achieved, movable component **MC** deflects towards substrate **3602**. Electrodes **SCE** and **MCE** can be electrically connected to a signal line **SL** for supplying a signal, typically AC, to variable capacitor **3600** from other electrical circuitry (not shown).

Figure 37B illustrates a top perspective view of another exemplary variable capacitor, generally designated **3704**, including a

suspended, movable component **MC**. Movable component **MC** can include movable actuation electrodes **MAE1** and **MAE2** and a movable capacitive electrode **MCE**. In this embodiment, electrodes **MAE1**, **MAE2**, and **MCE** are attached to a top surface of movable component **MC**. Alternatively, electrodes **MAE1**, **MAE2**, and **MCE** can be attached on the underside of movable component **MC** or on both the top and bottom surfaces. Actuation electrode **MAE** and capacitive electrode **MCE** can be electrically isolated via movable component **MC**.

Variable component **3704** can also include tethers **T1**, **T2**, **T3**, **T4**, and **T5** attached to movable component **MC** and posts (not shown) for suspending movable component **MC** above a substrate **3706**. Stationary actuation electrodes **SAE1** and **SAE2** can be disposed on the top surface of substrate **3706** and directly beneath movable actuation electrodes **MAE1** and **MAE2**, respectively. A stationary capacitive electrode (not shown) can be disposed on the top surface of substrate **3706** and directly beneath movable capacitive electrode **MCE**. A voltage supply **VS** can be connected at one terminal to movable actuation electrodes **MAE1** and **MAE2** and at another terminal to stationary actuation electrodes **SAE1** and

SAE2. Voltage supply **VS** can apply a potential difference between the movable actuation electrodes (**MAE1** and **MAE2**) and the stationary electrodes (**SAE1** and **SAE2**) such that, at after a voltage threshold V_T is achieved, movable component **MC** deflects towards substrate **3706**. The stationary capacitive electrode and movable capacitive electrode **MCE** can be electrically connected to a signal line **SL** for supplying a signal, typically AC, to variable capacitor **3704** from other electrical circuitry (not shown).

According to one embodiment, isolation bumps can be included with a variable capacitor (such as variable capacitor **400** shown in Figure 4) for preventing movable capacitive electrode (such as movable capacitive electrode **MCE2** shown in Figure 5) and/or movable actuation electrode (such as movable actuation electrodes **MAE3** and **MAE4** shown in Figure 5) from contacting a stationary capacitive electrode (such as stationary capacitive electrode **SCE** shown in Figure 5) and/or stationary actuation electrodes (such as stationary actuation electrodes **SAE1** and **SAE2** shown in Figure 5). The use of isolation bumps can enable variable capacitors with high capacitance ratio and electromechanical stability.

Figures 38 and 39 illustrate different cross-sectional side views of a variable capacitor having isolation bumps. Referring to Figure 38, a cross-sectional side view of a variable capacitor, generally designated **3800**, having isolation bumps **IP1**, **IP2**, and **IP3** is illustrated. Variable capacitor **3800** can include a movable component **MC** having movable actuation electrodes **3802** and **3804** positioned on a top and bottom surface **3806** and **3808**, respectively. Movable component **MC** can include movable capacitive electrodes **3810** and **3812** positioned on a top and bottom surface **3806** and **3808**, respectively. Variable capacitor **3800** can also include a substrate **3814** including a top surface **3816** having a stationary capacitive electrode **3818** deposited thereon.

Substrate **3814** can include one or more substrate layers, generally designated **SL**, including a stationary actuation electrode **3820** positioned therein. Substrate layers **SL** can also include a capacitor interconnect **CI** for connecting stationary capacitive electrode **3818** to a signal line (not shown). In this embodiment, substrate layers **SL** include a base substrate layer **BSL**, a first metal layer **M1**, a first substrate layer **S1**, a second metal layer **M2**, and a second substrate layer **S2**.

In this embodiment, one or more sacrificial layers (not shown) can be used during a fabrication process for constructing movable component **MC** (Figure 38). The sacrificial layers can subsequently be removed by a suitable process to form the gap, generally designated **G**, between movable component **MC** and substrate **3814**. In this embodiment, gap **G** can extend different distances between movable component **MC** and substrate **3814**. For example, a gap distance **D1** between movable actuation electrode **3804** and surface **3816** of substrate **3814** can be about 2.5 micrometers with a range between about 0.5 and 10 micrometers. In this embodiment, gap distance **D1** is the total of the following thicknesses: thickness of stationary capacitor **3818**, the thickness of a first sacrificial layer for forming gap **G**, and the thickness of a second sacrificial layer for forming gap **G**. Additionally, for example, a gap distance **D2** between isolation bump **IP1** and surface **3816** of substrate **3814** can be about 2.0 micrometers in the embodiment and can be somewhat smaller than the overall actuation gap limited only be the fabrication precision. In this embodiment, gap distance **D2** is the thickness of the first sacrificial layer. Additionally, for example, a gap distance **D3** between movable capacitive electrode

3812 and surface **3816** of substrate **3814** can be between about 0.5 and 20 micrometers. In this embodiment, gap distance **D3** is the thickness of the first and second sacrificial layers. Additionally, for example, a gap distance **D4** between isolation bump **IP2** and stationary capacitive electrode **3818** can be 2.0 micrometers and range from between about 0.5 and 20 micrometers. In this embodiment, gap distance **D4** is the thickness of the first sacrificial layer. Additionally, for example, a gap distance **D5** between isolation bump **IP3** and stationary capacitive electrode **3818** can be 2.0 micrometers and range from between about 0.5 and 20 micrometers. In this embodiment, gap distance **D5** is the thickness of the first sacrificial layer.

Referring to Figure 39, actuation voltage has been applied to actuation electrodes **3802**, **3804**, and **3820** for moving movable component **MC** to a closed position such that isolation bumps **IP1**, **IP2**, and **IP3** contact substrate **3814**. Isolation bumps **IP1**, **IP2**, and **IP3** can prevent movable capacitive electrode **3812** from contacting stationary capacitive electrode **3818**. In this embodiment, capacitive electrodes **3812** and **3818** can be separated by a distance of about

0.5 micrometers when movable component **MC** is in the closed position.

The equivalent actuation gap of the embodiment shown in Figures 38 and 39 is provided by the following equation (wherein S1 represents the thickness of first substrate layer **S1**, S2 represents the thickness of second substrate layer **S2**, M2 represent the thickness of second metal layer **M2**, SAC1 represents the thickness of the first sacrificial layer, SAC2 represents the thickness of the second sacrificial layer, M3 represents the thickness of stationary capacitive electrode **3818** and ks represents the relative dielectric constant of the substrate):

$$\text{Equivalent electrical gap} = \frac{S1 + S2 + M2}{ks} + SAC1 + SAC2 + M3$$

In this embodiment, the equivalent electrical gap is about 5 micrometers. In this embodiment, the mechanical displacement is limited to the thickness of the first sacrificial layer. The actuation voltage scales as V α airgap^(3/2). For an air gap of 1.5 micrometers, the actuation voltage is 15 Volts. With an equivalent air gap of 5 micrometers, the actuation voltage is 91 Volts. With the variable capacitor **400** (Figure 4) including isolation bumps such as isolation bumps **IP1**, **IP2**, and **IP3** shown in Figures 38 and 39, a

minimum capacitance of 0.5 picoFarads can be achieved. Additionally, in such a configuration, the capacitance ratio is about 4.

Referring to Figure 40, a cross-sectional side view of another variable capacitor, generally designated **4000**, having an isolation bump **IP** is illustrated. Variable capacitor **4000** can include a movable component **MC** having movable actuation electrodes **4002** and **4004** positioned on a top and bottom surface **4006** and **4008**, respectively. Movable component **MC** can include movable capacitive electrodes **4010** and **4012** positioned on a top and bottom surface **4006** and **4008**, respectively. Variable capacitor **4000** can also include a substrate **4014** including a top surface **4016** having a stationary capacitive electrode **4018** deposited thereon.

Substrate **4014** can include one or more substrate layers, generally designated **SL**, including a stationary actuation electrode **4020** positioned therein. Substrate layers **SL** can also include a capacitor interconnect **CI** for connecting stationary capacitive electrode **4018** to a signal line (not shown). In this embodiment, substrate layers **SL** include a base substrate layer **BSL**, a first metal layer **M1**, a first substrate layer **S1**, a second metal layer **M2**, and a second substrate layer **S2**.

In this embodiment, one or more sacrificial layers (not shown) can be used during a fabrication process for constructing movable component **MC** (Figure 40). The sacrificial layers can subsequently be removed by a suitable process to form the gap, generally designated **G**, between movable component **MC** and substrate **4014**. In this embodiment, gap **G** can extend different distances between movable component **MC** and substrate **4014**. For example, a gap distance **D1** between movable actuation electrode **4004** and surface **4016** of substrate **4014** can be about 2.5 micrometers with a range between about 0.5 and 10 micrometers. In this embodiment, gap distance **D1** is the total of the following thickness: thickness of stationary capacitor **4018**, the thickness of a first sacrificial layer for forming gap **G**, and the thickness of a second sacrificial layer for forming gap **G**. Additionally, for example, a gap distance **D2** between isolation bump **IP** and surface **4016** of substrate **4014** can be between about 0.5 and 20 micrometers. In this embodiment, gap distance **D2** is the thickness of the first sacrificial layer. Additionally, for example, a gap distance **D3** between movable capacitive electrode **4012** and surface **4016** of substrate **4014** can be about 2.0 and range from between about 0.5

and 20 micrometers. In this embodiment, gap distance **D3** is the thickness of the first and second sacrificial layers. The gap ratio is about 0.55 in this embodiment.

The equivalent actuation gap of the embodiment shown in Figure 40 is provided by the following equation (wherein S2 represents the thickness of second substrate layer **S2**, SAC1 represents the thickness of the first sacrificial layer, SAC2 represents the thickness of the second sacrificial layer, M3 represents the thickness of stationary capacitive electrode **4018** and ks represents the relative dielectric constant of the substrate):

$$\text{Equivalent electrical gap} = \frac{S2}{ks} + SAC1 + SAC2 + M3$$

In this embodiment, the equivalent electrical gap is about 3.3 micrometers. In this embodiment, the mechanical displacement is limited by the thickness of the first sacrificial layer. For an air gap of 1.5 micrometers, the actuation voltage is 15 Volts. With an equivalent air gap of 5 micrometers, the actuation voltage is 49 Volts. With the variable capacitor **400** (Figure 4) including isolation bumps such as isolation bump **IP** shown in Figure 40, a minimum capacitance of 0.5 picoFarads can be achieved. Additionally, in such a configuration, the capacitance ratio is about 4.

Referring to Figure 41, a cross-sectional side view of another variable capacitor, generally designated **4100**, having an isolation bump **IP** is illustrated. Variable capacitor **4100** can include a movable component **MC** having movable actuation electrodes **4102** and **4104** positioned on a top and bottom surface **4106** and **4108**, respectively. Movable component **MC** can include movable capacitive electrodes **4110** and **4112** positioned on a top and bottom surface **4106** and **4108**, respectively. Variable capacitor **4100** can also include a substrate **4114** including a top surface **4116** having a stationary capacitive electrode **4118** deposited thereon.

Substrate **4114** can include one or more substrate layers, generally designated **SL**, including a stationary actuation electrode **4120** positioned therein. Substrate layers **SL** can also include a capacitor interconnect **CI** for connecting stationary capacitive electrode **4118** to a signal line (not shown). In this embodiment, substrate layers **SL** include a base substrate layer **BSL**, a first metal layer **M1**, a first substrate layer **S1**, a second metal layer **M2**, and a second substrate layer **S2**.

Movable component **MC** can also include a planarization dielectric that is compatible with the process attached to bottom

surface **4108**. A exemplary dielectric choice is to use silicon dioxide for the planarization dielectric. This planarization oxide **PO** can be non-conductive for preventing movable capacitive electrode **4112** from electrically communicating with stationary capacitive electrode **4118**.

In this embodiment, one or more sacrificial layers (not shown) can be used during a fabrication process for constructing movable component **MC** (Figure 41). The sacrificial layers can subsequently be removed by a suitable process to form the gap, generally designated **G**, between movable component **MC** and substrate **4114**. In this embodiment, gap **G** can extend different distances between movable component **MC** and substrate **4114**. For example, a gap distance **D1** between movable actuation electrode **4104** and surface **4116** of substrate **4114** can be about 2.5 micrometers with a range between about 0.5 and 10 micrometers. In this embodiment, gap distance **D1** is the total of the following thickness: thickness of stationary capacitor **4118**, the thickness of a first sacrificial layer for forming gap **G**, and the thickness of a second sacrificial layer for forming gap **G**. Additionally, for example, a gap distance **D2** between isolation bump **IP** and surface **4116** of

substrate **4114** can be between about 0.5 and 20 micrometers. In this embodiment, gap distance **D2** is the thickness of the first sacrificial layer. Additionally, for example, a gap distance **D3** between planarization oxide **PO** and surface **4116** of substrate **4114** can be between about 0.5 and 20 micrometers. In this embodiment, gap distance **D3** is the thickness of the first and second sacrificial layers.

Regarding the embodiment shown in Figure 41, the unactuated capacitance value is about 0.6 picoFarads. The capacitance ratio in this embodiment is about 13. The higher ratio (greater than 3 times the above embodiments assuming silicon oxide as the planarization oxide) and higher maximum capacitance (greater than 4 times the above embodiments assuming silicon oxide as the planarization oxide) enabled by having a dielectric in the gap provide more control in the circuit and allow the use of smaller variable capacitors to provide the required function. Higher dielectric constant materials that are compatible with the process can also be utilized for the planarization oxide with greater gains in ratio and maximum capacitance.

Referring to Figure 42, a cross-sectional side view of another variable capacitor, generally designated **4200**, having isolation bumps **IP1** and **IP2** is illustrated. Variable capacitor **4200** can include a movable component **MC** having movable actuation electrodes **4202** and **4204** positioned on a top and bottom surface **4206** and **4208**, respectively. Movable component **MC** can include movable capacitive electrodes **4210** and **4212** positioned on a top and bottom surface **4206** and **4208**, respectively. Variable capacitor **4200** can also include a substrate **4214** including a top surface **4216** having a stationary capacitive electrode **4218** deposited thereon.

Substrate **4214** can include one or more substrate layers, generally designated **SL**, including a stationary actuation electrode **4220** positioned therein. Substrate layers **SL** can also include a capacitor interconnect **CI** for connecting stationary capacitive electrode **4218** to a signal line (not shown). In this embodiment, substrate layers **SL** include a base substrate layer **BSL**, a first metal layer **M1**, a first substrate layer **S1**, a second metal layer **M2**, and a second substrate layer **S2**.

In this embodiment, one or more sacrificial layers (not shown) can be used during a fabrication process for constructing movable

component **MC** (Figure 42). The sacrificial layers can subsequently be removed by a suitable process to form the gap, generally designated **G**, between movable component **MC** and substrate **4214**. In this embodiment, gap **G** can extend different distances between movable component **MC** and substrate **4214**. For example, a gap distance **D1** between movable actuation electrode **4204** and surface **4216** of substrate **4214** can be about 0.8 micrometers. Alternatively, distance **D1** can range between about 0.5 and 20 micrometers. In this embodiment, distance **D1** is the thickness of the first and second sacrificial layers. Additionally, for example, a gap distance **D2** between isolation bump **IP1** and surface **4216** of substrate **4214** can be about 0.3 micrometers. Alternatively, distance **D2** can range from between about 0.2 and 19 micrometers. In this embodiment, gap distance **D2** is the thickness of the first sacrificial layer. For the largest ratio, the second sacrificial layer should be as thin as is feasible with suitable thickness control. Additionally, for example, a gap distance **D3** between movable actuation electrode **4212** and stationary actuation electrode **4218** can be about 0.5 micrometers. Alternatively, distance **D3** can range from between about 0.2 and 20 micrometers.

In this embodiment, gap distance **D3** is the thickness of the first and second sacrificial layers after planarization to level the top of the sacrificial material to the level of the sacrificial material in the area where there is no portion of electrode **4218**. Additionally, for example, a gap distance **D4** between isolation bump **IP2** and stationary actuation electrode **4218** can be about 0.3 micrometers. Alternatively, distance **D4** can range between about 0.2 and 19 micrometers. In this embodiment, gap distance **D4** is the thickness of the first sacrificial layer.

Regarding the embodiment shown in Figure 42, the maximum capacitance value is about 5 picoFarads, and the minimum capacitance value is about 2 picoFarads. The capacitance ratio in this embodiment is about 2.5. In this embodiment, the actuation voltage at the maximum capacitance is about 15 Volts.

A variable capacitor according to one embodiment can include a rotatable movable component attached to one or more torsional beams for providing resistance to the rotational motion. The movable component can be attached to the torsional beam such that the movable component has two “free” ends for rotating about the torsional beam. One or more movable actuation electrodes can be

disposed on one end of the movable component. Additionally, one or more movable capacitive electrodes can be disposed on an opposing end of the movable component such that the attachment of the torsional beam is between the movable capacitive electrodes and the movable actuation electrodes. When the movable actuation electrodes are actuated, the movable actuation electrode can cause its corresponding end of the movable component to move downward and rotate the movable component about the torsional beams. Additionally, when the movable actuation electrodes are actuated, the opposing end of the movable component can move upward to displace the movable capacitive electrode from an associated stationary capacitive electrode for changing the capacitance of the variable capacitor.

Figures 43-45 illustrate different views of a variable capacitor, generally designated **4300**, including torsional beams **TB1** and **TB2**. Referring specifically to Figure 43, a top perspective view of variable capacitor **4300** is illustrated. Variable capacitor **4300** can include a substrate **4306** having a pair of spaced-apart pivot posts **P1** and **P2** supporting torsional beams **TB1** and **TB2**, respectively. Torsional beams **TB1** and **TB2** can support a movable component **MC** for

rotational movement of opposing ends of movable component **MC** about a pivot axis (generally designated with a broken line **4308** extending from a side of movable component **MC**). Torsional beams **TB1** and **TB2** can also provide resistance to the rotational movement of movable component **MC**. The center support of these torsional beams enables robust fabrication and operation of torsional variable capacitors using movable component **MC** layers with compressive intrinsic stresses.

Torsional beams **TB1** and **TB2** can provide vertical stiffness to limit vertical motion of movable component **MC** with respect to substrate **4306**. Further, torsional beams **TB1** and **TB2** can provide torsional softness to ease rotational motion of movable component **MC**. Figure 44A illustrates a cross-sectional side view of one embodiment of variable capacitor in the direction indicated by lines **L1** and **L2** (shown in Figure 43). Referring to Figure 44A, in this embodiment, torsional beams **TB1** and **TB2** (shown in Figure 43) can have a rectangular cross-section and a beam of sufficient length to provide flexibility. Alternatively, torsional beams **TB1** and **TB2** can have any suitable cross-section shape, dimension, or length. Additionally, torsional beams **TB1** and **TB2** can include folded

springs. Torsional beams **TB1** and **TB2** can comprise one or more layers of silica, alumina, un-doped semiconductors, polymers, and other non-conductive materials known to those of ordinary skill in the art.

Figure 44B illustrates a cross-sectional side view of an alternative embodiment of variable capacitor **4300**. In this embodiment, movable component **MC** comprises a first portion **4400** and a second portion **4402**, wherein second portion **4402** is positioned closer to substrate **4306** than first portion **4400**. Therefore, movable actuation electrodes (**MAE1** and **MAE2**) and stationary actuation electrode **SAE** can be positioned further apart than the distance between movable capacitance electrodes (**MCE1** and **MCE2**) and stationary capacitance electrode **SCE** to its attachment to first portion **4400** because movable actuation electrode **MAE** is positioned on raised first portion **4400**. The dual gap can be formed by two different thicknesses of sacrificial layer.

Referring to Figure 44C illustrates a cross-sectional side view of another alternative embodiment of variable capacitor **4300**. Stationary actuation electrode **SAE** can be buried in substrate **4306**. This positioning can increase the distance between stationary

actuation electrode **SAE** and movable actuation electrodes **MAE1** and **MAE2** without adding the complexity of additional sacrifical layers.

Substrate **4306** can also include a stationary actuation electrode **SAE** and a stationary capacitive electrode **SCE** formed on a surface **4310** thereof. Movable component **MC** can include movable actuation electrodes **MAE1** and **MAE2** attached to a top surface **4312** and a bottom surface **4314** (shown in Figure 44), respectively, of movable component **MC**. Movable actuation electrodes **MAE1** and **MAE2** can be positioned above stationary actuation electrode **SAE**. Movable actuation electrodes **MAE1** and **MAE2** can be attached to one terminal of a voltage supply (such as voltage supply **VS** shown in Figure 4) and stationary actuation electrode **SAE** can be attached to another terminal of the voltage supply for applying a potential difference to actuate variable capacitor **4300**. When actuated, movable actuation electrodes **MAE1** and **MAE2** can move towards stationary actuation electrode **SAE** for operatively moving movable component **MC** along pivot axis **4308**.

Substrate **4306** can also include a stationary capacitive electrode **SCE** attached to surface **4310**. Movable component **MC** can also include movable capacitive electrodes **MCE1** and **MCE2** attached to surfaces **4312** and **4314**, respectively. Capacitive electrodes **SCE**, **MCE1**, and **MCE2** can be electrically connected to a signal line (such as signal line **SL** shown in Figure 4) for supplying a signal to variable capacitor **4300** from other electrical circuitry (not shown). When variable capacitor **4300** is actuated to move movable component **MC** along pivot axis **4308**, movable capacitive electrodes **MCE1** and **MCE2** can be moved away from stationary capacitive electrode **SCE** to change the capacitance between stationary capacitive electrode **SCE** and movable capacitive electrodes **MCE1** and **MCE2**.

Referring to Figure 45, a cross-sectional side view of variable capacitor **4300** in an actuated mode is illustrated. Movable actuation electrodes **MAE1** and **MAE2** are positioned closer to stationary actuation electrode **SAE** than in an unactuated position as shown in Figures 43 and 44. Movable capacitive electrodes **MCE1** and **MCE2** are positioned further from stationary capacitive

electrode **SCE** than in the unactuated position shown in Figures 43 and 44.

Variable capacitor **4300** can achieve the specifications shown in Table 5 below.

Parameter	**Value**
$V_{control}$	4.5 V
Resonance frequency	2 kHz
C_{min}	0.9 pF
Capacitance ratio	1:2

Table 5: Summary of Specifications

The specifications indicated in Table 5 can be varied by changing the length of torsional beams **T1** and **T2** (Figure 43). A capacitance value of about 0.26 pF for variable capacitor **4300** can be obtained. Torsional beams **T1** and **T2** can have a length between about 25 and 175 micrometers. Figure 46 illustrates a graph showing the harmonic behavior for variable capacitor **4300** (Figures 43-45).

An important parameter effecting resonance frequency is rotational inertia of movable component **MC**. The rotational inertia of movable component **MC** equals the mass of movable actuation electrodes **MAE1** and **MAE2** and movable capacitive electrodes **SCE1** and **SCE2**. Figure 47 illustrates a graph showing the frequency response for different distances of movable actuation

electrodes **MAE1** and **MAE2** (Figure 43) and movable capacitive electrodes **SCE1** and **SCE2** (Figure 43) from pivot axis **4308** (Figure 43).

Figure 48 illustrates a top view of a schematic diagram of another examplary torsional variable capacitor, generally designated **4800**. Variable capacitor **4800** can include a movable capacitor **MC** having a top surface **4802**. A movable capacitance electrode **MCE** and a movable actuation electrode **MAE** can be attached to top surface **4802**. Variable capacitor **4800** can also include pivot posts **P1** and **P2** and torsional beams **TB1** and **TB2**. The dimensions of the components of variable capacitor **4800** are indicated in micrometers.

An array of variable capacitor such as variable capacitor **4300** shown in Figures 43-45 can be arranged in parallel to achieve different maximum and minimum capacitances. For example, sixteen variable capacitors (such as variable capacitor **4300**) can be arranged in parallel to achieve a maximum capacitance of 4 pF, a minimum capacitance of 2 pF, and a first resonance mode of 22. kHz. Figure 49 illustrates a computer simulation model of deformation of a torsional variable capacitor **4900** of an array of 16

variable capacitors (such as variable capacitor **4800** shown in Figure 28). The maximum displacement is located near movable capacitance electrode **MCE**.

Figure 50 illustrates a graph showing the capacitance of a torsional variable capacitor (such as variable capacitor **4300** shown in Figure 43) versus an applied actuation voltage.

Figure 51 illustrates a computer simulation model of deformation of a movable component of a torsional variable capacitor (such as variable capacitor **4300** shown in Figure 43) under a stress gradient between +1 and -1 MPa. The corners of movable component have a displacement of nearly 1 micrometer.

A torsional variable capacitor (such as variable capacitor **4300** shown in Figure 43) can include apertures in the movable component for decreasing the effects of damping. According to one embodiment, the apertures in a torsional variable capacitor can be up to three times larger than 5 micrometers.

Figure 52 illustrates a computer simulation model of the deformation of a movable component in a torsional variable capacitor (such as torsional variable capacitor **4300** shown in Figure 43) for an acceleration of 100g. The displacement of the outer edge

of movable capacitance electrode **5200** is about –0.09 micrometers. For a 0.3 g acceleration, the displacement of the outer edge of movable capacitance electrode **5200** is about 0.27 nanometers, resulting in a capacitance change of less than about 0.05%.

When a long conductive line is used to connect two or more torsional variable capacitors (such as torsional variable capacitor **4300** shown in Figure 43) in parallel, the overall RF performance of the configuration can be downgraded. In particular, the inductance added by the connection can lower the self-resonance frequency.

Table 6 below indicates a summary of specifications for 16 torsional variable capacitors (such as variable capacitor **4300** shown in Figure 44) connected in parallel.

Parameter	**Value**
$V_{control}$	27 V
Resonance frequency	22.4 kHz
C_{min}	0.12 pF x 16
Capacitance ratio	maximum 1:2
R(dc)	≈1.5 ohms
Vibration sensitivity	0.05% for 0.3 g
Stress sensitivity	negligible
Stress gradient deformation (for +/- 1 MPa)	-1 μm
Cut-off frequency	Un-Damped System

Table 6: Specification Summary

Figure 53 illustrate a computer simulation model RF results of computer simulation model for an equivalent circuit of a torsional variable capacitor (such as variable **4300** shown in Figure 43). Referring to Figure 53, the HFSS electro-magnetic, full-wave simulator (available from Ansoft Corporation of Pittsburgh, Pennsylvania) can be used for modeling a torsional capacitor. Referring to Figure 53, the resonance quality Q and Smith chart, generally designated **5300**, of a torsional variable capacitor (such as variable **4300** shown in Figure 43) is shown.

It will be understood that various details of the subject matter disclosed herein may be changed without departing from the scope of the subject matter. Furthermore, the foregoing description is for the purpose of illustration only, and not for the purpose of limitation.